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Fiber Optic Sensing System for Temperature and Gas Monitoring in Coal Waste Pile Combustion Environments

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ABSTRACT

It is presented an optical fiber sensing system projected to operate in the demanding conditions associated with coal waste piles in combustion. Distributed temperature measurement and spot gas sensing are requirements for such a system. A field prototype has been installed and is continuously gathering data, which will input a geological model of the coal waste piles in combustion aiming to understand their dynamics and evolution. Results are presented on distributed temperature and ammonia measurement, being noticed any significant methane emission in the short time period considered. Carbon dioxide is also a targeted gas for measurement, with validated results available soon. The assessment of this technology as an effective and reliable tool to address the problem of monitoring coal waste piles in combustion opens the possibility of its widespread application in view of the worldwide presence of coal related fires.

Keywords: Extreme environments, burning coal waste piles, fiber optic sensing systems, temperature and gas sensing.

1. INTRODUCTION

The occurrence of coal related fires is known all over the world and is associated with coal mining, disposal of coal mining residues, coal transportation, and coal storage. Coal related fires represent geological extreme environments due to the high burning temperatures, that could easily reach more than 1000 °C very close to the surface (at less than 1 m depth), and due to the gaseous emissions that may contain high concentrations of volatile organic compounds and greenhouse gases. The environmental impacts associated with the coal related fires include the emission of harmful gases and particulate matter into the atmosphere, mobilization and leaching of hazardous elements and formation of coal fires gas minerals, causing pollution of air, soils and sediments, surface and groundwater's, and negative effects on human health and biodiversity^{1,2}. The monitoring of combustion temperature and gaseous emissions is particularly needed for the identification of the impacts on environment and human health, the establishment of probable evolution scenarios, and for the definition of timely corrective measures to minimize the negative impacts. Previous studies dealt only with measurements in specific points, i.e., measurements that are not distributed in space and continuous in time. Aiming the remote, multi-point and continuous measurement of combustion temperature and gaseous emissions in self-burning waste piles, a R&D INTERREG-SUDOE project entitled ECOAL-MGT- ("Ecological Management of Coal Waste Piles in Combustion") is being developed, with participation of groups from Portugal, Spain and France. In this project, a fiber sensing system is being used for the first time in this environment. The results will allow: i) understanding of spontaneous combustion and self-burning mechanisms, in coal fires, including evolution scenarios and dynamics of the processes; ii) identification of potential environmental and human health impacts; iii) identification and implementation of mitigation procedures to minimize the impact on the environment, the human health impact and the loss of natural resources; and, iv) contribution to avoid the occurrence of spontaneous combustion and self-burning processes. After laboratory development of a fiber optic based optoelectronic sensing system for distributed temperature and gas emission measurement, a prototype has been installed in a self-burning coal waste pile located in S. Pedro da Cova (Porto, Portugal). The system is gathering data that will input geological models to assess the status of the coal waste pile. Here,

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it is presented a brief description of this coal deposit, the structure of the fiber optic sensing system developed and, finally, results relative to the measurement of distributed temperature and gas emission are delivered.

2. CASE STUDY - S. PEDRO DA COVA COAL WASTE PILE

A self-burning coal waste pile located in S. Pedro da Cova (Porto, Portugal) was selected for the implementation of the ECOAL-MGT project. The S. Pedro da Cova coal waste pile resulted from the past mining activities in Douro Coalfield and started burning in 2005 after intense forest fires in the region, which caused their ignition. This waste pile has an area of approximately 28 000 m² and is located close to the oldest center of mining activities in S. Pedro da Cova and near to a population community and social infrastructures. This coal waste pile was selected for the field implementation of the ECOAL-MGT project due to its proximity to a residential area and also due to the knowledge already attained about the geological characteristics of the material that constitutes the coal waste pile. The prototype installation included the creation of small platforms (1 m width) along a restricted area of the coal waste pile in which the combustion process seems to be more intense (Figure 1A). To support the prototype design, its installation and the continuous measurement of temperature and gaseous emissions, the monitoring of temperature in the surface of the coal waste pile is being performed monthly since February 2013, using infrared thermography. Figure 1B illustrates the thermographic image acquired in February 2015 where it is identified the main focus of combustion process.

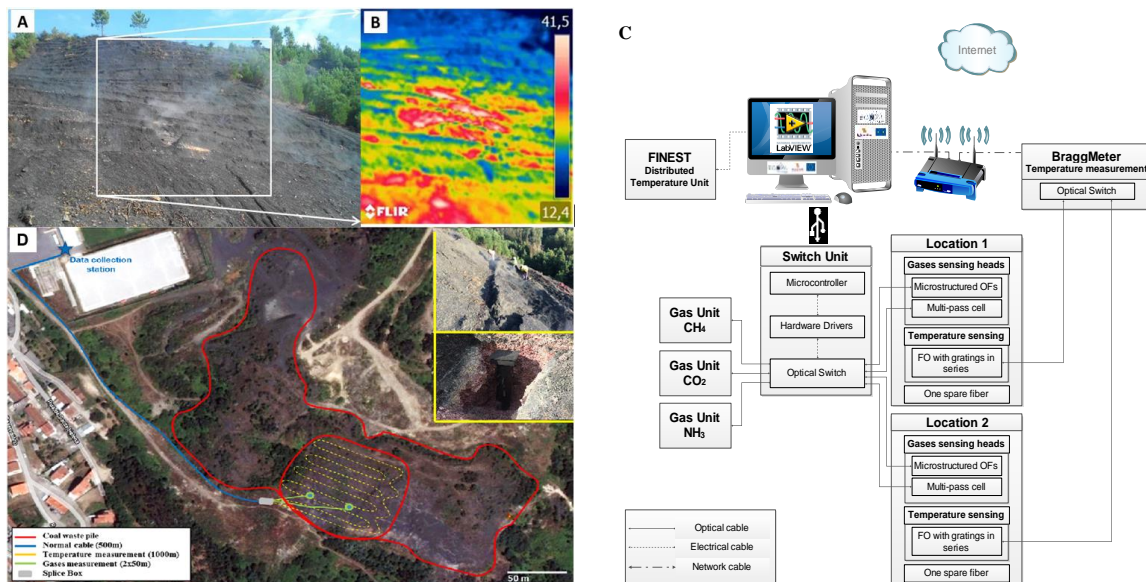


Figure 1. A - General view of the area under combustion where is visible the platforms along the slope and the gaseous emissions; B - Thermographic image used for preliminary temperature characterization of the region. C - General architecture of the optical fiber sensing system for gas and temperature measurement in coal waste piles; D - Aerial view of S. Pedro da Cova coal waste pile (red contour), showing: i) region of distributed temperature measurement (yellow line); ii) gas measurements spots (green points); iii) optical fiber cable path to the central office; iv) installation of the fiber optic cable for distributed temperature measurement (right, top); v) installation of one of the boxes to accommodate the gas sensors (right, middle).

3. OPTICAL FIBER SENSING SYSTEM

The general architecture of the fiber optic sensing system is shown in Figure 1C. For distributed temperature measurement, Brillouin Optical Time-Domain Analysis (BOTDA) is proposed to monitor the pile, with a single-mode fiber layout extended over the whole area of the waste pile in combustion. Having in mind the targeted application, a special optical cable that stands high temperature was used (*BRUsens Temperature sensing cable 5.0mm HDPE*, provided by Brugg). The cable for distributed measurement was buried at 10 to 20 cm depth along the slope platforms. As two fibers are used in the measuring cable, redundant measurements are obtained in each position. The temperature estimation is therefore achieved by averaging the results obtained from the two independent measurements realized in the same position. The BOTDA architecture used in this case is essentially similar to the conventional systems described in the literature³, except that the proposed system incorporates balanced detection⁴. Balanced detection provides substantial advantages in this case as it eliminates common-mode noise, provides an improved signal-to-noise ratio over the conventional single-detector systems and provides a method to eliminate polarization noise in the BOTDA signal by

employing orthogonal probe sidebands⁵. It also provides a better use of the dynamic range of the detector as it avoids saturation and allows higher input powers. High spatial resolution measurements are performed using the differential pulse-width pair technique⁶. This technique overcomes the conventional time-frequency trade-offs encountered in traditional BOTDA by subtracting the gain profiles obtained in the same position with slightly different pulse lengths. A resolution of 0.5 m is thus obtained subtracting the results obtained with 52 and 47 ns pulses.

In terms of gas sensing, a sensing system in the near infrared region has been developed for the detection of ammonia, carbon dioxide and methane based on wavelength modulation spectroscopy (WMS). WMS is a rather sensitive technique for detecting atomic/molecular species, presenting the advantage that it can be used in the near-infrared region by employing optical telecommunication technology⁶. The technique consists in applying a sine wave modulation signal, at a frequency of a few kHz, superimposed on the laser bias current. This modulates simultaneously both the wavelength and the intensity of the laser light. The modulated laser light interacts with the absorption line of the target gas and, with proper processing, the amplitude of the second harmonic of the modulation frequency is proportional to the gas concentration³. The optoelectronic gas sensing system is composed by two types of sensing heads. One based on free light propagation, with a 160 cm of optical path length, and another based on microstructured optical fibers (in development) with gases diffusing in their holes. This allows redundant operation and technology validation. In order to have flexibility on the optical power levels, the sensing system incorporates the functionalities of optical amplification and attenuation. For gas measurement, two different spots in the coal waste pile were selected (Figure 1D). In one of these spots (the left spot in Figure 1D), besides gas sensing heads, was installed a Fiber Bragg Grating (FBG) based sensor system with three temperature measurement points at different heights. The system installation was concluded in February 2015, thereafter starting a global testing procedure which is yet under way. Therefore, the results delivered next section may be considered preliminary, with planning of their consolidation to be performed next months.

4. RESULTS

A comprehensive set of temperature measurements in the coal waste pile were accomplished over several weeks. In Figure 2A we depict a measurement of the temperature profile for the complete fiber length. It can be observed that, as mentioned above, each point is measured twice obtaining a symmetrical profile and, so, measurement redundancy. The temperature data are easily extracted from the measured BFS by using the sensitivity of the BFS to temperature. Figure 2B shows a detail of 250 m of three different temperature profiles taken along one week, of which two are performed consecutively in the same day. The two profiles obtained during the same day (orange and grey lines in Figure 2B) show good agreement between them, highlighting the repeatability of the BOTDA system. The other temperature profile displayed in the Figure 2B (blue line) was performed a week before than others. As it can be seen, some temperature peaks present in the blue line do not appear in the orange and grey lines. Remarkably, these results show rapid bursts of high temperature in the pile, which are presumably associated to the spontaneous release of hot gas at certain positions. These outcomes can be very helpful in the exploration of geological models of pile evolution.

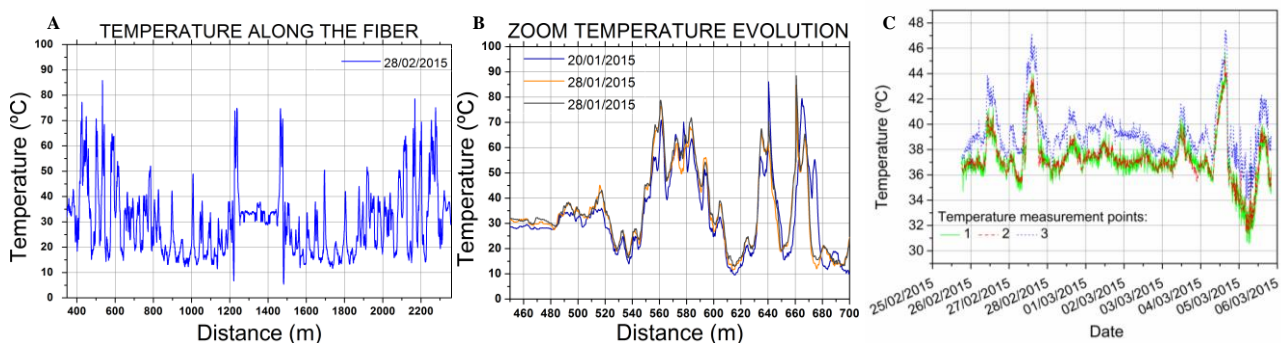


Figure 2. A - Temperature profile along the optical fiber in the coal pile. B - A detail of one week evolution of the temperature profile along the optical fiber in the coal pile. C - Point temperature measurements in the leftmost green spot in Figure 1D.

The rapid evolution of the temperature over the pile was confirmed by temperature point measurements using FBGs. Figure 2C shows the temperature measured by the FBG system at three points, located at the depths of 1.3, 1.4 and 1.5 m, during approximately 10 days (from 25th February to 5th March 2015). Even at a reduced scale, the dynamics of the burning coal pile is also imprinted in this data, with a temperature amplitude variation of $\sim 18^{\circ}\text{C}$ observed in the period considered. The Figure also shows that a depth increase of 20 cm leads to a temperature rise of $\sim 10\%$.

At this gas measurement spot, it was found residual the emission of methane in the period 12-17 March 2015 (illumination with a DFB laser emitting at 1653.72 nm). The same did not happen concerning ammonia, with detection associated with the light emitted by a DFB laser operating at 1512.21 nm. The measurement is done using the multi-pass cell sensing head with 160 cm of optical path length. As shown in Figure 3A, ammonia concentration (volume) evidences a strong daily variation, in some periods of the day reaching 0.6-0.7% and in some others decreasing to residual values (a zoom for one day evolution is shown in Figure 3B). A longer series of data is required to identify the main features of this behavior and, as a consequence, to determine the factors that are in their origin. For detection of carbon dioxide it is considered a DFB laser emitting at 1572 nm. The results obtained so far need to be calibrated and cross checked, a task which is underway.

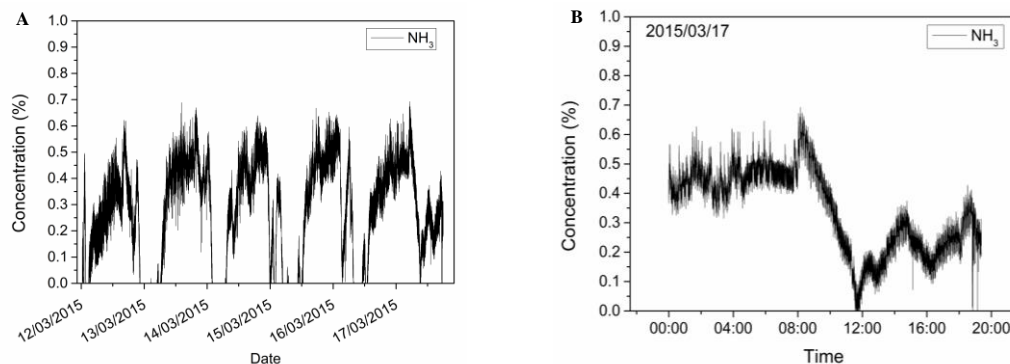


Figure 3. A - Evolution of ammonia concentration during five days in the left gas spot of Figure 1C; B - Detail of variation along a day (March 17th).

5. CONCLUSIONS

In conclusion, it was presented an optical fiber sensing system suitable for monitoring coal waste piles in combustion. Distributed temperature measurement and spot gas sensing were achieved, using BOTDA and WMS technology in each case. A field prototype has been installed and is continuously gathering data, which will be used as input to a geological model of the coal piles in combustion. This model will help in understanding the coal waste pile dynamics and evolution. Results were presented distributed temperature and ammonia measurement, being noticed any significant methane emission in the short time period considered. Carbon dioxide is also a targeted gas for measurement, with validated results available soon. The assessment of this technology as an effective and reliable tool to address the problem of monitoring coal waste piles in combustion opens the possibility of its widespread application in view the worldwide presence of coal related fires.

6. ACKNOWLEDGMENTS

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